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Dependence of noise temperature on physical temperature for cryogenic low-noise amplifiers

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Abstract. We present the results of noise-temperature measurements for four radio astronomy MMIC low-noise amplifiers (LNAs) at physical temperatures from 2 to 160 K. We observe and confirm recent reports that the noise temperature of an LNA exhibits a quadratic dependence with respect to the physical temperature. We are also able to confirm the prediction by Pospieszalski that below a certain physical temperature there is no further significant reduction in noise temperature. We then discuss these results in the context of both the Pospieszalski noise model and some recent Monte–Carlo simulations, which have implied that at very low temperatures, heating of the electron channel above ambient temperature may help to explain the behavior of the drain temperature parameter. [DOI: 10.1117/1.JATIS.3.1.014003]

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1 Introduction

Low-noise amplifiers (LNAs) are a key component in many of the receiver systems that are used for radio astronomy. The LNA's gain is typically provided by several indium phosphide (InP) high electron mobility transistors (HEMTs) that are either placed individually into a microwave integrated circuit (MIC) or more commonly fabricated within a monolithic microwave integrated circuit (MMIC). These LNAs are often then cooled to ∼20 K, since this results in nearly an order of magnitude improvement in their overall noise temperature.

For MIC LNAs, several studies[1–5] have previously looked at the dependence of noise on the physical temperature at temperatures as low as 12 K. These studies showed either a "weak" quadratic dependence or a linear dependence with respect to the physical temperature. To our knowledge, however, no such study exists for MMIC LNAs. Neither has a study been conducted for either type at temperatures as low as 2 K.

Therefore, some of the authors undertook such an investigation for a prototype Planck Ka-band MIC LNA,[6] observing that the noise temperature continued to decrease below 20 K. This paper initially presents the results of a similar study for four MMIC-based radio astronomy LNAs, then discusses these results, showing how they support the findings of a recent study investigating the intrinsic temperature of the HEMT's conduction channel,[7] and finally considers the implications of these findings for future radio astronomy receivers.

2 Noise and Physical Temperature

There are several models that can be used for modeling the noise behavior of an HEMT; one that has proved particularly effective is the Pospieszalski noise model.[8] This shows that the standard four noise parameters can be expressed in terms of an HEMT's equivalent circuit parameters and two frequency-independent noise temperatures. The first parameter, T_g, is associated with the gate-source resistance r_{gs}, while the second, T_d, is associated with the drain-source conductance g_{ds}. It is generally accepted[9] that for situations where the gate leakage current is low, T_g scales linearly with temperature, while T_d is independent of temperature (except for low drain currents) and instead scales linearly with the drain current.[10] T_g and T_d are approximately related[8] to the minimum noise-temperature parameter T_{min} by

$$T_{min} \simeq 2\frac{f}{f_t}\sqrt{r_{gs}g_{ds}T_dT_g}\,, \tag{1}$$

with $f_T = g_m/2\pi C_{gs}$, where C_{gs} is the gate-source capacitance and g_m is the transconductance. Pospieszalski[11] has also shown that T_{min} is related to the noise temperature (T_n) by Eq. (2), where T_0 is the standard temperature (290 K), Z_s and Z_{opt} are the source and optimum source impedances, R_s and, R_{opt} are the source and optimum source resistance, and $N = G_nR_{opt}$, with G_n the noise conductance.

$$T_n = T_{min} + NT_0\frac{|Z_s - Z_{opt}|^2}{R_sR_{opt}}. \tag{2}$$

Accordingly, using amplifiers that have been designed for low noise, i.e., $Z_s \approx Z_{opt}$, we can use T_n as a proxy for T_{min}, which allows us to use measurements of the LNA's noise temperature to comment on the temperature behavior of T_{min}. Therefore, if we assume that the temperature dependence of the equivalent circuit parameters is small[12] and that T_d is independent of temperature, from Eqs. (1) and (2) we would expect T_{min} and hence T_n to be proportional to the square root of the physical temperature. However, the assumption that T_d is independent of

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temperature has been questioned by several authors, with both linear[12] and quadratic[1,13,14] relationships being proposed.

Pospieszalski[8] has also shown that in the very low temperature limit where $T_g \to 0$, $T_{\min}$ can be expressed as

$$T_{\min}(0) \approx 4\left(\frac{f}{f_T}\right)^2 r_{gs} g_{ds} T_d, \tag{3}$$

which is taken to be the nonthermal noise contribution from the hot electron noise that arises due to the conduction electrons undergoing heating via the electric field at the foot of the gate. As a consequence of this result, we would expect that at very low physical temperatures, a further reduction in the temperature should lead to no further significant improvement in the LNA's noise temperature. Both Pospieszalski and Pucel[15] have also commented that the hot electron noise may partly explain the difference in the behavior of the T_g and T_d parameters.

3 Test System and Low-Noise Amplifiers

Our cryogenic system[6] consists of a vacuum vessel and a two-stage (40 and 3 K) pulse tube cooler. Further cooling is provided by a ^{4}He sorption-pumped stage, with a no-load base temperature of 1 K. However, because of the heat dissipated by the DUT, the actual minimum physical temperature achieved is ∼1.6 K. Diode and ruthenium oxide thermometers are used to monitor the physical temperature. The DUT temperature is varied using a heater (resistor) and a variable temperature waveguide load is connected to the input of the LNA and used as a hot and cold noise source. The noise test setup consisted of an HP/Agilent 8350B sweep generator, with an 83550A plug-in module and an 83554A mm-wave source module providing an LO to a downconverting mixer, and an 8970B noise figure meter connected to the IF. The Y-factor technique is then used to calculate the noise temperature.

Four LNAs were used in this study; LNA 1, which was developed as part of the European FARADAY project,[16] is based around a four-stage InP MMIC. LNA 2 utilizes a three-stage InP HEMT MMIC.[17] LNA 3 is a commercial low noise MMIC LNA from the Low Noise Factory (Sweden).[18] LNA 4[19] exhibits both MIC and MMIC technologies since it comprises both an InP Cryo-3 HEMT[20] and a Faraday MMIC, with the HEMT placed discretely in front of the MMIC. All four LNAs were designed for operation at Ka-band and their mean noise temperatures were measured for a 20% bandwidth, centered on the frequency corresponding to minimum noise. As per earlier studies,[1,3] the LNAs were biased for minimum noise at 20 K, and the same drain voltages and drain currents were used for all measurements. Details of the bias settings used by the LNAs, the geometries of the transistors, and the foundry process used are provided in Table 1.

Table 1 Gate width (l_w), gate length (l_g), and bias settings for the first stage transistor. The original foundry process for each of the LNAs is also shown.

LNA	l_g (nm)	l_w (μm)	V_d (V)	I_d (mA)	Foundry
1	100	4 × 30	0.9	5	NGST
2	100	4 × 15	0.7	8.5*	NGST
3	100	4 × 25	1.2	9*	LNF and Chalmers
4	100	4 × 20	1.2	2	TRW†

*Subsequently became NGST.
†Current is drawn by all three stages.

4 Noise Temperature Versus Physical Temperature

The noise temperature with respect to the physical temperature for each of the LNAs is shown in Fig. 1. Like the earlier studies,[1–4] we are also able to report what appears to be a "weak" quadratic relationship between noise temperature and physical temperature. The cooling of the LNAs to very low temperatures also shows that below 10 to 20 K, depending on the amplifier, the noise temperature effectively ceases to decrease, an observation that supports the low-temperature prediction of the Pospieszalski model [Eq. (3)]. There are also hints from Fig. 1 that the temperature at which this transition occurs is related to the noise temperature of the device, with the transition occurring at lower physical temperatures for lower noise devices. This is a characteristic that should be considered when deciding on the operating temperature of a receiver, especially in light of the availability of cryocoolers with base temperature of 4 K.

5 Drain Temperature and Physical Temperature

Using the above results, we are also able to comment on some recent Monte–Carlo simulations[7] that looked at the thermodynamic properties of the HEMT region described by the T_d parameter. The simulations showed that above ∼25 K, the conduction channel is effectively thermalized with the LNA's module. Below this temperature, however, phonon transport is unable to cool the HEMT's conduction channel and it remains hotter than its surroundings, limiting the improvement in noise temperature that can be achieved through cooling. By analyzing the data presented in this paper in a similar style to that used in Schleeh et al.,[7] we can also comment on the behavior of the T_d parameter. Figure 2 again shows the noise temperature with respect to the temperature of the modules for LNAs 1, 2, and

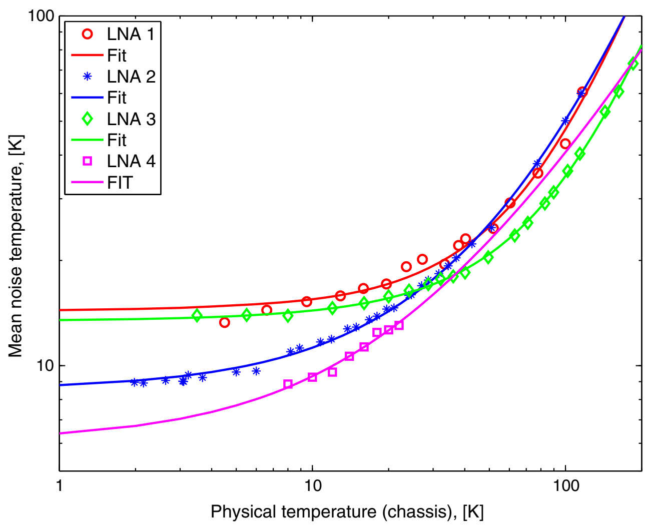

Fig. 1 The measured mean noise temperature (for a 20% bandwidth) of the four LNAs at range of physical temperatures. A quadratic best fit (fitted by MATLAB®) is also shown for each LNA. For LNA 4, stability issues above ∼20 K restricted the noise measurements to a limited temperature range.

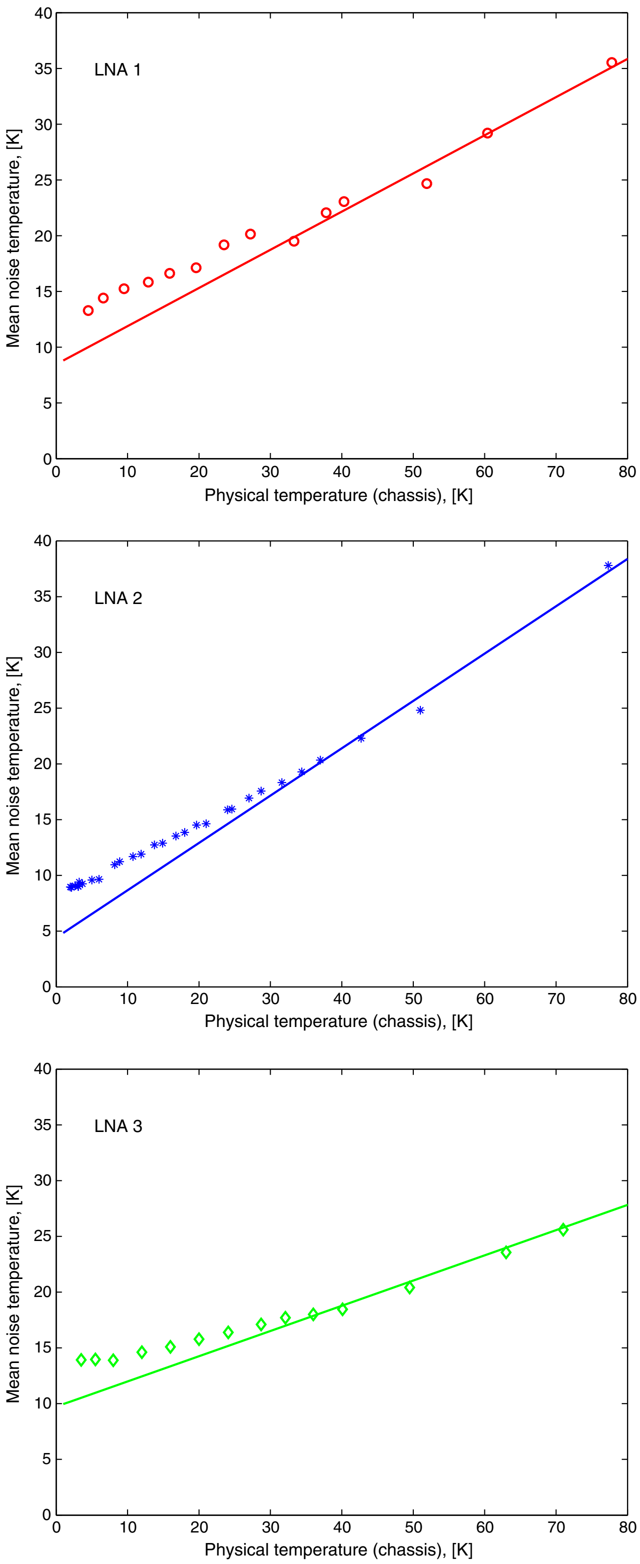

Fig. 2 The noise temperature of each LNA shown on a linear scale from 2 to 80 K. The trend lines were fitted for all data points above 30 K. LNA 4 is not shown as the amplifier was found to be unstable above ∼25 K.

3; a linear fit for all data points above 30 K is also shown. Since T_g's dependence on temperature is known to be linear, to account for the linear behavior of T_n it is likely that, within this temperature regime, T_d also has a linear dependence on temperature. Below 20 to 25 K, however, Fig. 2 shows that the data points do not follow the extrapolation, a result that is also reported for the 12-GHz LNA used in the Monte–Carlo studies. This deviation is likely due to the conduction channel remaining hotter than its surrounding environment, causing T_d to lose its linear temperature dependence, with the result that the noise temperature tends to the low temperature case [Eq. (3)].

6 Conclusion

This paper has looked at the relationship between the noise temperature of MMIC LNAs and the physical temperature of the surrounding environment. By cooling LNAs to temperatures below 10 K and then comparing the results with recent Monte–Carlo simulations, we have been able to show that while this relationship at first sight appears quadratic in nature, it is linear for most temperatures. We have also been able to support a recent interpretation of this behavior as an inability to cool the transistor's electron channel to the temperature of the surrounding components, which causes the T_d temperature parameter to progressively lose its temperature dependence below 25 K. Therefore, future device development needs to focus on reducing the self-heating of the channel, for example by minimizing the required drain current, which should help reduce T_d. As previously suspected, there is also a physical temperature below which no further significant improvement in noise temperature is observed. However, this temperature is LNA-dependent and may be below the typical operating temperatures (∼20 K) of most of today's radio telescopes. Therefore, radio astronomy observatories should consider taking advantage of the widespread availability of 4 K cryocoolers and consider lowering the operating temperature of their receivers to around 10 K. This result also supports a prediction by Pospieszalski that when cooled to temperatures where T_g can be assumed to be effectively zero, a residual temperature is reached that is still substantially larger than the expected contribution from quantum noise.

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